

## Advances in Shell Buckling: Theory and Experiments\*

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In a recent feature article in this journal, coauthored by Gert van der Heijden, I described the static-dynamic analogy and its role in understanding the localized post-buckling of shell-like structures, looking exclusively at integrable systems. We showed the true significance of the Maxwell energy criterion load in predicting the sudden onset of “shock sensitivity” to lateral disturbances. The present paper extends the survey to cover nonintegrable systems, such as thin compressed shells. These exhibit spatial chaos, generating a multiplicity of localized paths (and escape routes) with complex snaking and laddering phenomena. The final theoretical contribution shows how these concepts relate to the response and energy barriers of an axially compressed cylindrical shell.

After surveying NASA’s current shell-testing programme, a new nondestructive technique is proposed to estimate the “shock sensitivity” of a laboratory specimen that is in a compressed metastable state before buckling. A probe is used to measure the nonlinear load-deflection characteristic under a rigidly applied lateral displacement. Sensing the passive resisting force, it can be plotted in real time against the displacement, displaying an equilibrium path along which the force rises to a maximum and then decreases to zero: having reached the free state of the shell that forms a mountain-pass in the potential energy. The area under this graph gives the energy barrier against lateral shocks. The test is repeated at different levels of the overall compression. If a symmetry-breaking bifurcation is encountered on the path, computer simulations show how this can be suppressed by a controlled secondary probe tuned to deliver zero force on the shell.

**Keywords:** Maxwell load; shell buckling theory; shell buckling experiments; shock sensitivity; localization; imperfection sensitivity; stability; rods.

### 1. Introduction

Early in the 20th century the pioneering use of thin metal shells as load-carrying components in aircraft and rockets stimulated engineers to look in detail at two well-defined archetypal problems of elastic buckling. These were the complete spherical shell subjected to uniform external pressure, and the cylindrical shell subjected to uniform axial compression. In careful laboratory tests, both of these were found to be collapsing violently at about

one quarter of the classical buckling loads,  $P_C$ , predicted by small-deflection linear theory. In response to this discrepancy, von Karman and Tsien [1939, 1941] made approximate Rayleigh–Ritz analyses to demonstrate that, for both problems, there exists a very unstable, subcritical post-buckling path of periodic equilibrium states. This falls rapidly from  $P_C$  and eventually stabilizes at a fold (limit point) at what they termed the *lower buckling load*,  $P_L$ . They suggested that this load might be a useful

\*Based on the opening lecture at the IDEAS Workshop, “Investigating Dynamics in Engineering and Applied Science”, celebrating Gábor Stépán’s 60th birthday, July 3–5, 2014, Budapest.

# Advances In Shell Buckling Theory And Experiments

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